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EFFECT OF AERATION BASIN CONFIGURATION ON BULKING AT LOW ORGANIC LOADING

by

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16. ABSTRACT

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This study was directed towards a further understanding and definition of the effect of aeration basin configuration on activated sludge bulking at low F/M values. The study was conducted in well-controlled laboratory-scale activated sludge systems with nine different aeration basin contigurations.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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ABSTRACT

Continuous-flow laboratory-scale activated sludge units were operated on domestic sewage at low F/M. In CSTR units at the F/M range of 0.05-0.25 g COD removed/g TMLVSS, day, bulking did not occur with a weak (BOD_5 = 139 mg/L) sewage feed and TMLSS = 1.5 g/L. Supplementation of sewage by blending with raw sludge produced a stronger sewage (BOD_5 = 315 mg/L) which caused TMLSS to increase to 3.5 g/L. Bulking occurred in CSTR, 2, 4, 8, and 16 compartment units. An aeration basin with initial compartment 1/32nd of aeration basin volume prevented but did not cure bulking. An aeration basin with initial compartments 1/74th of aeration basin volume, prevented and cured bulking. Anoxia in an aeration basin with two initial compartments each 1/64th of the total aeration basin volume did not aid in curing bulking. The SVI of sludges at low F/M (0.3-0.35 g COD removed/g TMLVSS, day) and high TMLSS (3.5 g/L) is related to conditions in the initial compartment rather than those in the remainder of the aeration basin. Initial compartment soluble COD, first-compartment F/M, and initial compartment size are important; floc loading, dispersion number and total number of aeration basin compartments are not important.

This report is submitted in fulfillment of Grant No. R806107 by the Sanitary Engineering and Environmental Health Research Laboratory, University of California, Berkeley, under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from October 1, 1978 to January 31, 1981; work was completed as of June 30, 1981.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BOD_5	--	5-day biochemical oxygen demand (mg/L)
COD	--	chemical oxygen demand (mg/L)
CSTR	--	continuous flow stirred tank reactor
DO	--	dissolved oxygen concentration (mg/L)
F/M	--	food to microorganism ratio (also: substrate removal rate, organic loading) (g COD removed/g TMLVSS, day)
g	--	gram
Kg	--	kilogram
Km	--	kilometer
L	--	liter
MCRT	--	mean cell residence time
mg	--	milligram
mL	--	milliliter
MLSS	--	mixed liquor suspended solids concentration = mass TSS in aeration basin/volume of aeration basin (g/L)
Sol. COD_i	--	soluble COD in initial compartment
SS	--	suspended solid
SVI	--	sludge volume index (mL/g)
SVI_a	--	sludge volume index at TSS concentration = a
TMLSS	--	total mixed liquor suspended solids concentration = mass TSS in aeration basin and clarifier/volume of aeration basin and clarifier (g/L)
TMLVSS	--	total mixed liquor volatile suspended solids = mass VSS in aeration basin and clarifier (g)
TSS	--	total suspended solids concentration (mg/L)
VSS	--	volatile suspended solids concentration (mg/L)
V_T	--	total aeration basin volume
V_i	--	volume of initial compartment

SYMBOLS

D/uL	--	dispersion number
σ^2	--	variance — the square of the spread of the distribution
$NaHCO_3$	--	sodium bicarbonate

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TYPING GUIDE SHEET

SECTION 1

INTRODUCTION

Filamentous activated sludge bulking is caused by the presence of large amounts (greater than 10 km/gSS)* of various types of filamentous organisms extending from the activated sludge floc (Sezgin, et al., 1978; Palm, et al., 1980). Bulking has many causes; the types of filamentous organisms present can be useful in indicating the cause of bulking. Strom and Jenkins (1979), using the key of Eikelboom (1975, 1977) have found Sphaerotilus natans and Types 1701, 021N and 1863 to be characteristic of plants with aeration basin dissolved oxygen (DO) too low for the applied organic load (F/M); Microthrix parvicella and Types 0041, 0092, 0581 and 1851 were associated with plants having low F/M. The remedy for low DO sludge bulking is to increase aeration basin oxygenation capacity or lower the F/M and is guided in principle by the work of Palm, et al. (1980) which established a relationship between F/M and minimum DO to prevent (or cure) S. natans bulking.

Direct remedy of low F/M bulking usually is not possible because low F/M may be required for nitrification, by designer preference, or because of lower than anticipated wastewater flows.

Previous work (Chudoba, et al., 1973a, 1973b, 1974; Heide and Pasveer, 1974; Rensink, 1974; Houtmeyers, 1978; Tomlinson and Chambers, 1976, 1978) suggests that the growth of filamentous organisms at low F/M is suppressed in systems that either have a low degree of longitudinal mixing ("plug flow") or are provided with a short detention time initial compartment where sewage feed and return activated sludge are mixed. The mechanism of filamentous organism suppression is not clear. Suggestions include: lower filamentous organism growth rate compared to floc formers at high substrate levels (Chudoba, et al., 1973b); inability of filamentous organisms to store substrate for later use in growth (Houtmeyers, 1978; Rensink, et al., 1977); and lower substrate utilization rate of filamentous organisms compared to floc formers (Houtmeyers, 1978). Eikelboom (1981) recently has used the term "biosorption" to lump all of these factors together with physical incorporation of particulate and soluble substrates into the floc. He proposes that filamentous organism growth in activated sludges with high "biosorption capacity" can be suppressed by use of high initial "floc loading" values (mg COD/g MLVSS).

The work reported in this report was directed towards a further understanding and definition of the effect of aeration basin configuration on activated sludge settling at low F/M values. The data of Palm, et al. (1980) were used as a guide to set F/M and aeration basin DO concentrations to prevent low DO bulking.

*amount of filaments measured in kilometers per gram of suspended solids

SECTION 2

CONCLUSIONS

These conclusions are specific to City of Richmond, California, settled domestic sewage and settled sewage supplemented by mixing with raw sludge; they also are specific to activated sludge systems with a recycle ratio of 1.

1. Bulking at low F/M (0.05-0.25 g COD removed/g TMLVSS, day) did not occur when CSTR activated sludge systems were fed either fresh or stale unsupplemented settled domestic sewage and TMLSS was in the range 1.0-1.7 g/L.

2. As soon as supplemented settled sewage was fed to CSTR activated sludge systems at F/M in the range 0.15-0.2 g COD removed/g TMLVSS, day, bulking occurred.

3. The conditions existing in the zone of initial mixing between activated sludge and wastewater are important in determining whether or not filamentous bulking occurs at low F/M.

4. The degree of longitudinal mixing (as measured by the dispersion number) and the soluble COD gradient throughout the reactor do not appear to be important in determining whether or not filamentous bulking occurs at low F/M.

5. The F/M in the initial aeration basin compartment was found to be consistently related to final SVI while floc loading (Eikelboom, 1981) did not show such a relationship.

6. An aeration basin configuration consisting of 16 compartments, the first 8 of which are 1/32nd of the total aeration basin volume, will prevent low F/M filamentous bulking from occurring in a non-bulking sludge. This aeration basin configuration will not cure low F/M filamentous bulking in already bulking sludge. Because conditions in the initial compartment appear to be important (rather than the gradient of condition throughout the entire aeration basin) it is proposed that this conclusion can be applied to an aeration basin configuration with two initial compartments each 1/32nd of the total basin volume followed by a large CSTR with a volume equal to 30/32nds of the total basin volume.

7. An aeration basin configuration consisting of 16 compartments, configured as follows: compartments 1 and 2 equal to 1/74th of total

aeration basin volume; compartments 3-8 equal to 1/32nd of total aeration basin volume and compartments 9-16 equal to 1/10th of the total aeration basin volume, will both prevent and cure low F/M bulking. Again this conclusion is postulated to apply to a system consisting of two initial basins each 1/74th of the total basin volume followed by a large CSTR with a volume equal to 72/74ths of the total basin volume.

8. An aeration basin configuration consisting of two oxygenated (DO = 4.5 mg/L) initial compartments each 1/64th of the total basin volume followed by a CSTR equal to 62/64ths of the total basin volume produced a modest reduction in the SVI (measured at 2.5 g TSS/L) of a bulking sludge from 400 mL/g to 173 mL/g at low F/M. An identically-configured system with anoxic (stirred, N_2-flushed) initial compartments did not influence bulking at low F/M any differently from a control CSTR. It is therefore concluded that initial mixing zones for control of low F/M bulking should be aerated.

9. Critical values of initial compartment parameters for control of low F/M bulking for this waste are: soluble COD $\geq$ 80 mg/L, F/M in the first reactor $\geq$ 20 g COD removed/g MLVSS, day. Further work is needed to generalize these values and account for the effect of variables such as waste characteristics, recycle ratio, MLSS concentration, etc.

10. The filamentous organisms most commonly occurring in the compartmentalized units at F/M values of approx. 0.3 g COD removed/g TMLVSS, day were Type 021N and Thiothrix sp.; in the CSTR system and the more highly loaded compartmentalized systems Type 1701 and S. natans also occurred. Both the compartmentalized systems and the CSTR systems at lower F/M values contained Types 0041 and 0961. These results generally are consistent with those of Chudoba (1973a) and also suggest that the data presented here will be generally applicable to the management of bulking caused by Type 021N.

SECTION 3

RECOMMENDATIONS

The results produced by this study suggest several further lines of investigation that might lead to a better definition of the factors that contribute to the causes and the cures of activated sludge bulking at low F/M.

For a basic understanding of the bulking problem, there is no substitute for the fundamental approach of isolating the causative organisms, characterizing their metabolism and determining the factors that cause their growth in activated sludge. From such data clues should become evident that will allow the association of various waste characteristics and treatment variables to the excessive growth of these organisms. Continuous pure and defined mixed culture work should be a part of such investigations.

From a more empirical process standpoint, further work needs to be performed in defining process variables that affect activated sludge bulking at low F/M. The work reported here was conducted with one type of sewage, largely at one F/M and at a constant recycle (RAS) rate. The effect of variations in these and other treatment variables on low F/M bulking needs to be studied. The effect of whether or not anoxic selectors are appropriate needs further investigation.

Since the research has shown that relatively simple modifications to an aeration basin can have dramatic effects on sludge settleability it may be profitable to develop a demonstration project in which the curing of a low F/M bulking sludge is attempted by aeration basin compartmentalization.

SECTION 4

MATERIALS AND METHODS

Experiments were laboratory-scale using systems with acrylic plastic aeration basins of total volumes that ranged from 10.5 L (for the completely-mixed (CSTR) units) to up to approx. 80 L for various compartmentalized aeration basin units (Figure 1). Mixing was by paddles to produce a mean velocity gradient of 85 sec^{-1} exclusive of aeration. Total mixing intensity was increased by a maximum of 10 percent over that provided by stirring alone when house air was used for aeration; it was unchanged relative to stirring alone when pure oxygen was used for aeration. Air for aeration was cotton-filtered and water-saturated. Oxygen was supplied from cylinders through two-stage regulators and was water-saturated. Both were dispersed by porous diffusers. DO in the CSTR control units and in up to 5 of the initial compartments of the other aeration basin configurations was controlled by a feedback system consisting of a galvanic oxygen electrode, DO analyzer, and a recorder-controller that operated a solenoid valve on the air or O_2 supply line. A control range of approx. -0 mg/L and +1.0 mg/L relative to the desired minimum DO concentration was achieved. Air was supplied at a rate of 0.25 L/min to non-DO controlled compartments in 8 and 16-compartment configurations.

Secondary clarifiers were inverted Erlenmeyer flasks with their bottoms cut off and in some cases with an acrylic plastic cylinder attached. Clarifier capacities were varied according to aeration basin capacity as follows: 2.4L for 10.5L aeration basin, 6L for 40L aeration basin, 10.5L for 56-58L aeration basins, and 9.3-10.5L for 80L aeration basin.

Bronze or nichrome wires bent to conform to the conical portion of the inner clarifier walls and rotated at 1 rpm, were used to aid thickened sludge flow to the recycle lines. Both influent sewage and return sludge were dosed into the aeration basin with peristaltic pumps. The ratio of return sludge (RAS) flowrate to influent flowrate was 1.0. Sludge was wasted directly from the aeration basin. Systems were operated at ambient temperature which varied between 18-24°C.

Systems were characterized by V_T/V_i ratio (V_T = total aeration basin volume, V_i = volume of initial aeration basin compartment) and by dispersion number, determined from Rhodamine B slug addition tracer studies on the aeration basin only with no secondary clarifier or RAS stream. Effluent was sampled at 15-min. intervals (approx. 3.5% of average hydraulic detention time). From the tracer curve, Dispersion Number, D/uL, was calculated from the following equation using the Newton-Raphson iteration technique:

$$\sigma^2 = 2(D/uL) - 2(D/uL)^2[1 - \exp(-uL/D)] \qquad (1)$$

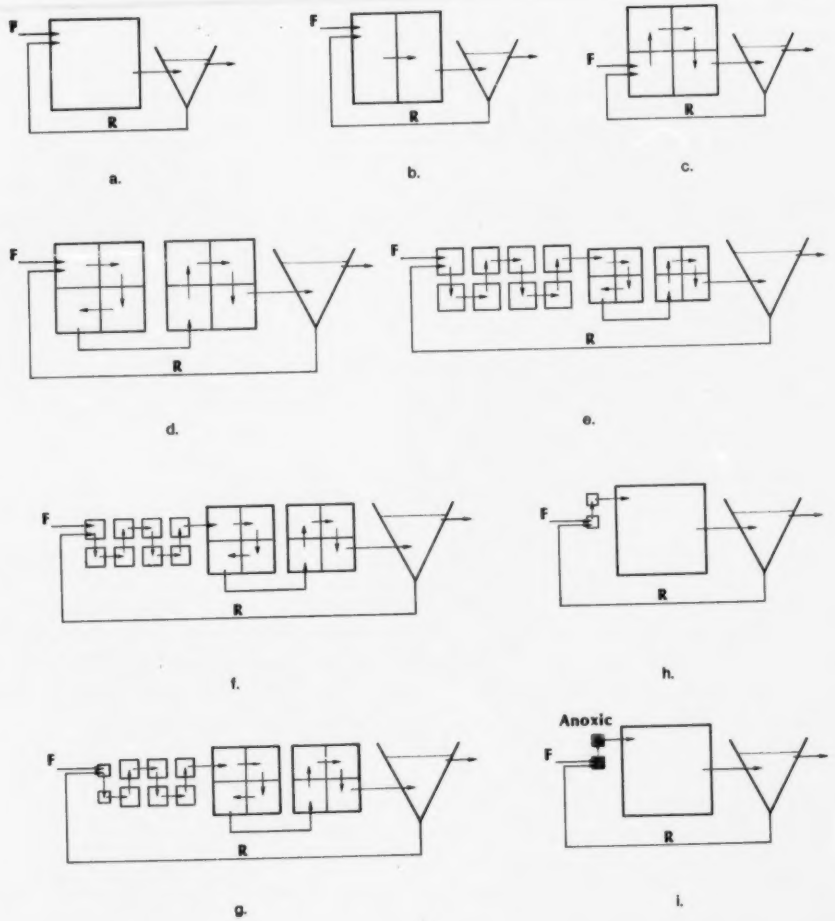

Figure 1. Aeration basin configurations used. Values of V_T/V_i are given in ().

a. CSTR system (1); for CSTR control, 10.5 L aeration basin; for 1 compartment system, 40-L aeration basin.
b. 40-L aeration basin, 2 compartments (2).
c. 40-L aeration basin, 4 compartments (4).
d. 80-L aeration basin, 8 compartments (8).
e. 56-L aeration basin, 16 equal-size compartments (16).
f. 58-L aeration basin, 16 compartments (32); first 8 are each equal to 1/32nd of total aeration basin volume and the next 8 are equally sized.
g. 58-L aeration basin, 16 compartments (74); first two are each equal to 1/74th, the next 6 are each equal to 1/32nd of total aeration basin volume and the last 8 are equally sized.
h. 42-L aeration basin, 3 compartments (64); first two are each equal to 1/64th and the following one compartment is equal to 62/64th of total aeration basin volume.
i. 42-L aeration basin, 3 compartments (64); same as i, but two initial compartments are anoxic.

Where σ^2 = determined value of variance (second moment of residence time distribution)(van der Laan, 1958; Levenspiel, 1962).

Analytical Methods

BOD_5, TSS and VSS were by Standard Methods (1975); COD was by Standard Methods (1975) with a 1 hr reflux time that was shown to yield values 98-100% of thos using a 2 hr reflux time; soluble COD was on Whatman GF/C filtered samples: NH_3-N was by the Solorzano method (Solorzano, 1969); nitrite/nitrate nitrogen was by copper-cadmium reduction (EPA, 1974) and total Kjeldahl nitrogen was by digestion-distillation (EPA, 1974). F/M was calculated as:

$$F/M = \frac{\text{Total COD in (g/day) - Soluble COD out (g/day)}}{\text{TMLVSS (g)}}$$

Where COD in = COD of feed
COD out = COD of effluent
TMLVSS = aeration basin VSS, g + clarifier VSS, g.

Clarifier VSS was performed on the mixed contents of the clarifier. Filamentous organisms were characterized by the key of Eikelboom (1977).

SECTION 5

RESULTS

Five series of experiments were conducted. In the first series CSTR aeration basins (Figure 1a) were operated at several steady states in the F/M range 0.05-0.25 g COD removed/g TMLVSS, day. Experiments commenced with non-bulking sludge. At all F/M values tested the CSTR did not produce a bulking sludge (Figure 2); neither was bulking sludge produced when the settled sewage feed was made stale (septic) by storage at room temperature for 2.5 days. Tomlinson and Chambers (1978) had suggested that stale sewage could promote filamentous organism growth. In these experiments, the rather weak Richmond settled sewage was the feed stock. (BOD_5 = 139 mg/L, COD = 300 mg/L, TSS = 75 mg/L). Because of the weak feed, TMLSS levels were in the range 1.0-1.7 g/L.

Previous work on bulking at low F/M (Chudoba, et al., 1973a, 1973b; Tomlinson, et al., 1976, 1978) was conducted with stronger influent wastes and thus higher MLSS concentrations resulted for an equivalent F/M. Also, Houtmeyers (1978) observed that a continuously-fed, one-compartment activated sludge system produced bulking sludge at MLSS=4 g/L but not when MLSS was 1 g/L. Because of this, the strength of the Richmond settled sewage feed was increased by blending it with raw sludge settled from the same sewage in the SERL pilot plant primary clarifier. Blending was as follows: mix settled sewage with 15% by volume raw sludge for 1.5 hr; settle 30-45 min.; mix supernatant and settled sewage in approx. equal volumes. A comparative analysis of Richmond settled sewage and the supplemented feed (Table 1) shows that while BOD_5 increased from 139 to 315 mg/L and COD increased from 300 to 750 mg/L, the BOD_5/COD ratio and the soluble fractions of BOD_5 and COD were similar. All other experiments were conducted with supplemented sewage.

The second series of experiments was conducted largely at F/M 0.15-0.20 g COD removed/g TMLVSS, day and TMLSS 3.0-3.5 g/L. Two parallel CSTR aeration basin systems were operated (Figure 1a), one receiving stale supplemented sewage and the other being fed with fresh supplemented sewage. Starting with a non-bulking sludge (SVI $\leq$ 100 mL/g), bulking (SVI $\geq$ 150 mL/g) occurred after 35 days in both systems when TMLSS concentration reached 3.0 g/L (Figure 3). Thereafter the two activated sludge systems were operated on fresh supplemented sewage feed. Following the demonstration that fresh supplemented sewage feed produced bulking, the first activated sludge system was designated as a CSTR control. The second unit was operated at steady-state with an aeration basin divided progressively into 2, 4, 8, then 16 equal-sized compartments. Sewage feed and RAS always entered the first compartment. As Figure 3 shows, compartmentalization to 16 equal-sized compartments did not improve sludge settleability over the control CSTR.

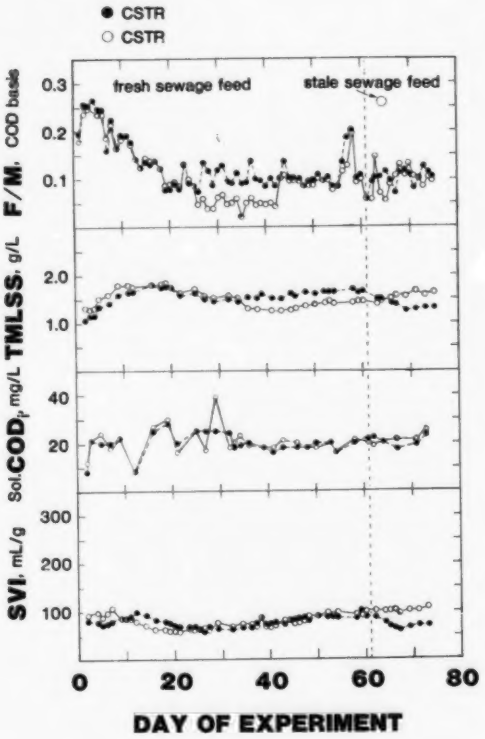

Figure 2. Experimental data: first series of experiments. Starting with a non-bulking sludge, bulking does not occur in a CSTR (TMLSS ≃ 1.5 g/L), F/M in range 0.05-0.25 g COD removed/g TMLVSS, day, using either fresh or stale unsupplemented Richmond settled sewage feed.

The third series of experiments employed a CSTR control (Figure 1a) and a 16 equal-sized compartment aeration basin (Figure 1e). Both units were operated at steady-state F/M values in the ranges 0.15-0.20, 0.20-0.25, 0.35-0.45, 0.5-0.6, 0.6-0.8, 0.9-1.15 and 1.15-1.4 g COD removed/g TMLVSS, day. For the F/M values, 0.15-0.20, 0.20-0.25, 0.35-0.45 and 0.5-0.6 the activated sludge initially was bulking (Figure 4); for the F/M values, 0.6-0.8, 0.9-1.15 and 1.15-1.4 the control and 16-compartment unit were started with non-bulking sludge from a laboratory batch system. Figure 4 shows that while sludge in the 16-compartment unit bulked somewhat later than that in the CSTR control, bulking was not prevented at any of these F/M ranges by aeration basins with 16 equal-size compartments. At the lower F/M values it was concluded that bulking could not be cured by use of a 16 equally-sized compartment aeration basin.

Because the use of a 16 equal-size compartment aeration basin did not prevent or cure bulking at any of the F/M values tested in the third series

TABLE 1. TYPICAL COMPOSITION OF RICHMOND SETTLED AND SUPPLEMENTED SEWAGE

Component	Settled*	Supplemented*
COD		
Total, mg/L	300	750
Particulate, %	52	48
Soluble, %	48	52
BOD_5		
Total, mg/L	139	315
Total COD/BOD_5	2.2	2.4
Kjeldahl Nitrogen		
Total, mg/L	38	46
Particulate, %	14	25
Soluble, %	86	75
Suspended Solids		
Total, mg/L	75	173
Volatile, %	67	67

*$NaHCO_3$ (approx. 400 mg/L) was added to the sewage feed to provide buffer capacity. This maintained aeration basin pH in the range 6.5-7 in the presence of complete nitrification.

of the experiments, it was decided to return to an F/M value of 0.3 g COD removed/g TMLVSS, day, and examine the effect of utilizing initial compartments smaller than 1/16th of the total aeration basin volume. The first 8 compartments were reduced in size to the desired fraction of the total aeration basin volume; the last 8 compartments were sized so that the total aeration basin volume was 56-58 L. This type of system is referred to as a "selector" configuration. At all times a CSTR control was run in parallel. All units were operated at F/M 0.3 g COD removed/g TMLVSS, day, TMLSS = 3.0-3.5 g/L and with fresh supplemented settled sewage feed.

A selector configuration of 8 compartments each 1/32nd of the total aeration basin volume (Figure 1f), prevented bulking while the CSTR control bulked (Figure 5, Days 0 to 26). At this point (Day 26) the test unit aeration basin was changed back to 16 equal-sized compartments (Figure 1e), and the control CSTR unit was restarted with non-bulking sludge. Again the CSTR bulked. The unit with 16 equal-size compartments also bulked, but less rapidly than the CSTR control (see Figure 5, Days 27 to 58).

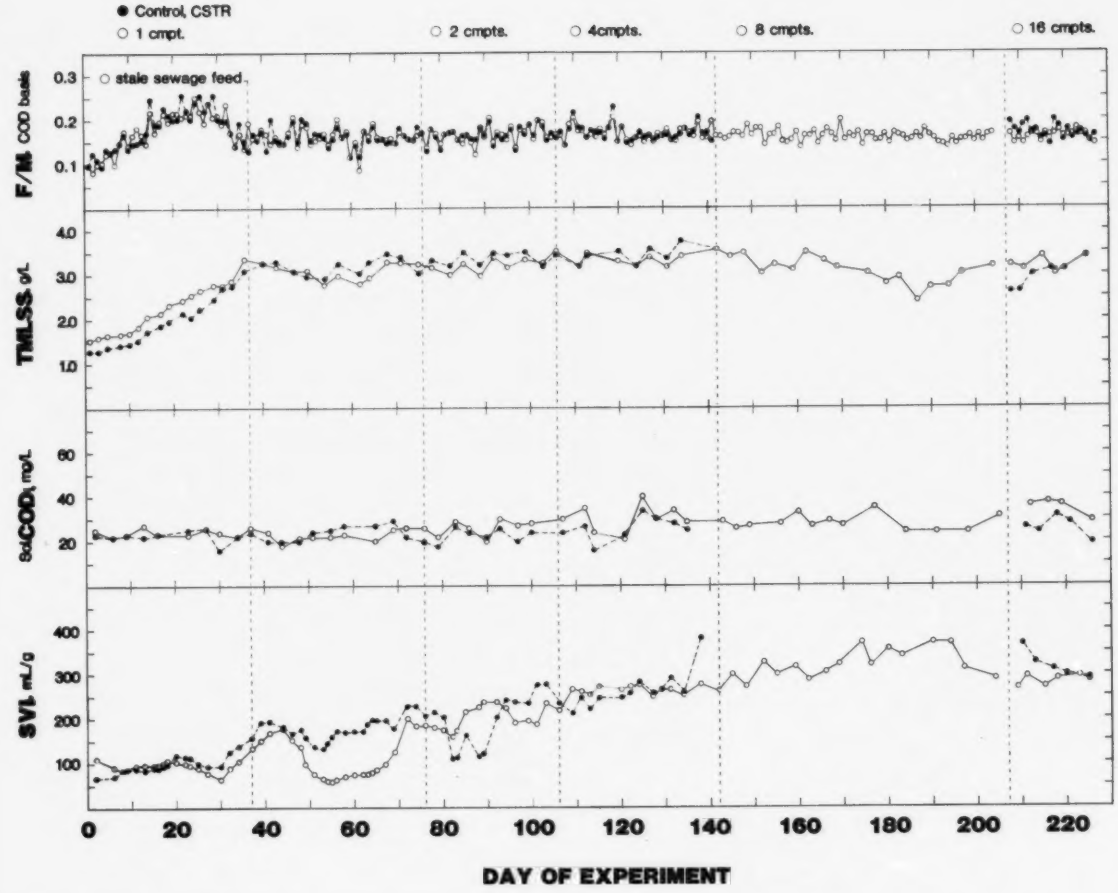

Figure 3. Experimental data; second series of experiments. Starting with a non-bulking sludge and either fresh or stale supplemented sewage feed, bulking occurred at TMLSS = 3-3.5 g/L, F/M = 0.15-0.20 g COD removed/g TMLVSS, day. Compartmentalization of aeration basin successively into 2, 4, 8 and 16 equal-size compartments operated with RAS and sewage both entering the first compartment did not cure the bulking.

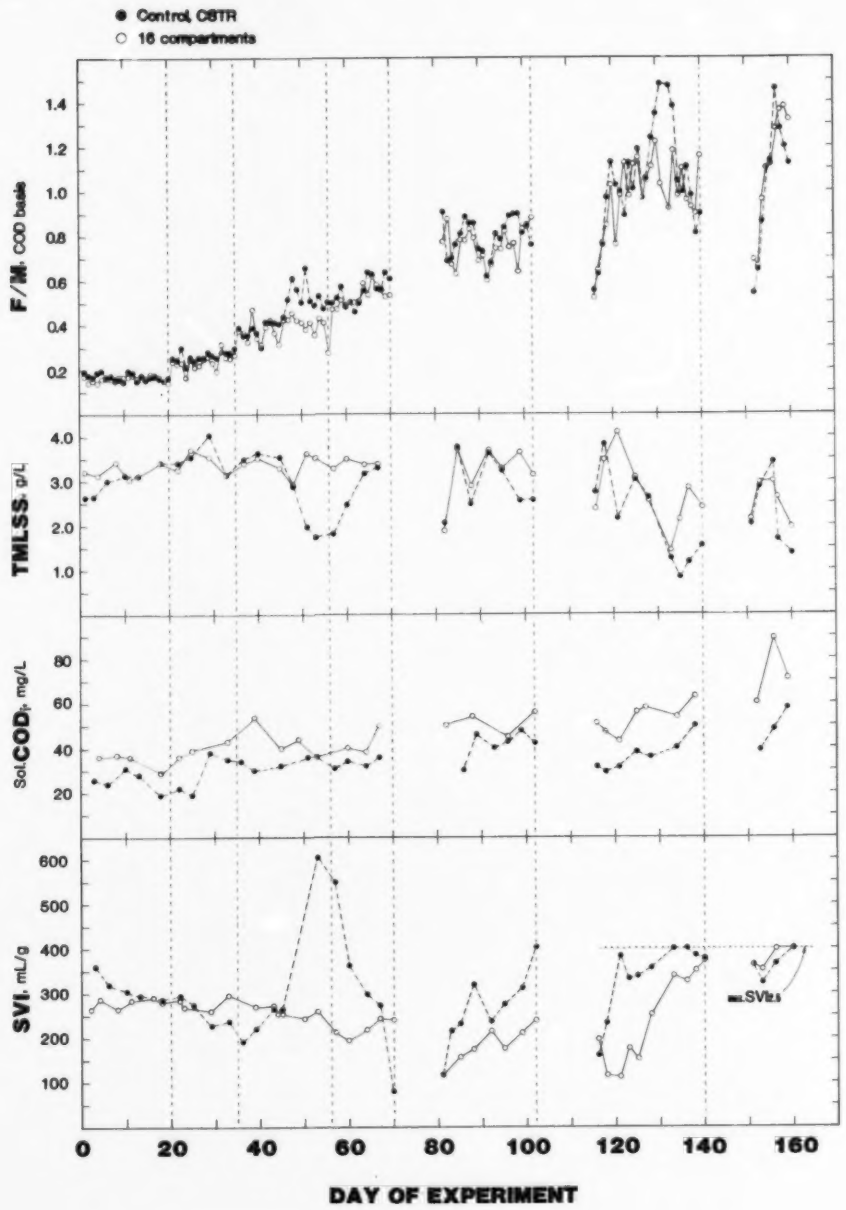

Figure 4. Experimental data; third series of experiments. With a 16 equal-size compartment aeration basin, and RAS and sewage fed to the 1st compartment, F/M was raised progressively from, 0.15-0.20 to 0.2-0.25, 0.35-0.45, 0.5-0.6, 0.6-0.8, 0.9-1.15, 1.15-1.4 (all g COD removed/g TMLVSS, day). Bulking either was not cured or not prevented at all F/M values tested.

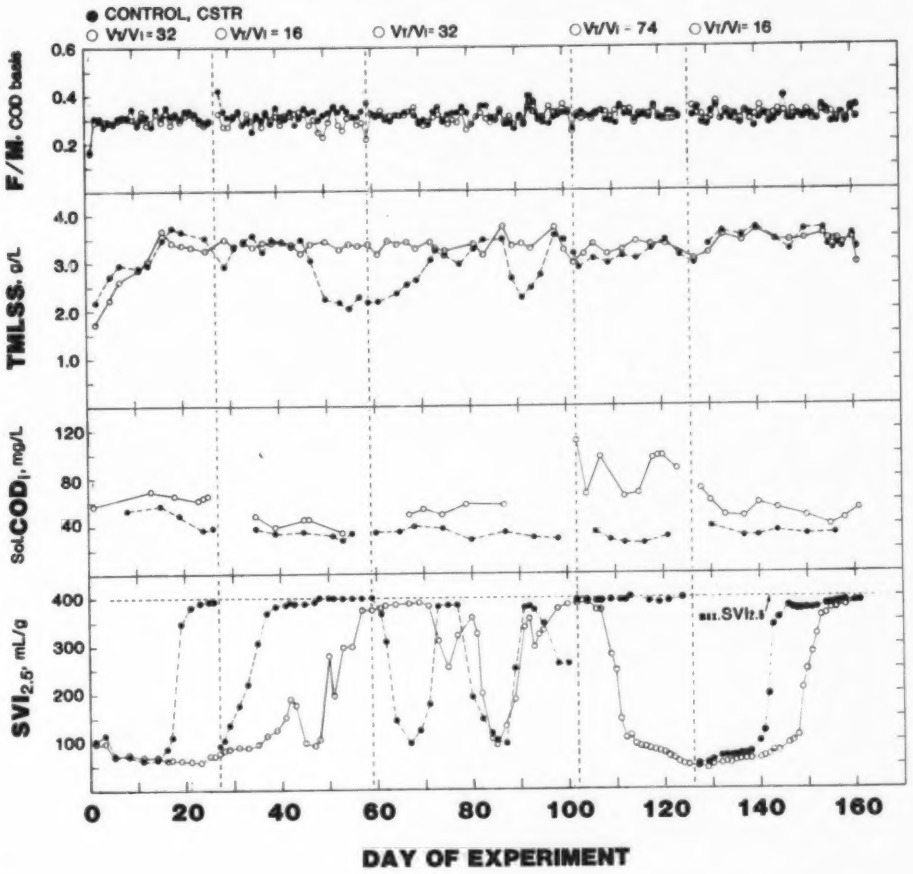

Figure 5. Experimental data; fourth series of experiments. The first eight compartments were converted to selector units. (V_T = total aeration basin volume; V_i = volume of initial compartment).

The system with 16 equal-size aeration basin compartments (Figure 1e) was returned to a selector configuration with the first 8 compartments, each 1/32nd of the total aeration basin volume (Figure 1f). This selector configuration, which had previously prevented the bulking of a non-bulking sludge did not cure an already-bulking sludge. The SVI of the selector unit and control unit fluctuated widely, but were similar to each other (Figure 5, Days 59-101).

At this point it was planned to change the selector configuration so that the first 2 compartments were 1/64th of the total aeration basin volume, the following 6 compartments were 1/32nd of the total aeration basin volume and the last 8 compartments were equally-sized to give a total aeration basin volume of 58L (Figure 1g). However, a measurement error resulted in

the first 2 compartments being 1/74th of the total aeration basin volume. Starting with a bulking sludge, this selector configuration rapidly reduced SVI while the CSTR continued to bulk (at maximum SVI). (Figure 5, Days 102 to 124).

The unit with the selector configuration containing non-bulking sludge was changed to a 16 equal-size compartment aeration basin (Figure 1e); the control CSTR was restarted with non-bulking sludge. Both units bulked (Figure 5, Days 127 to 161) as previously at this configuration (Figure 5, Days 27 to 58). Again the control CSTR bulked somewhat more rapidly than the unit with the 16 equal-sized compartments.

At this stage for F/M = 0.3 g COD removed/g TMLVSS, day, it had been deduced that:

a. An aeration basin with 16 equal-size compartments offered little advantage over a CSTR in preventing or curing bulking.

b. A 16-compartment aeration basin with its first 8 compartments each equal to 1/32nd of the total aeration basin volume would prevent bulking (when a CSTR bulked) but was not effective in curing bulking.

c. A 16-compartment aeration basin with its first 2 compartments each equal to 1/74th (at the time of the experiment this was thought to be 1/64th) of the total aeration basin volume would both prevent and cure bulking while an equivalently operated CSTR would bulk or not be cured from bulking.

Because the 16-compartment unit, with 2 initial compartments equal to 1/74th of the total aeration basin volume (thought to be 1/64th at the time) was successful in both preventing and curing bulking, it was decided to determine whether the same results could be obtained when the 2 initial selectors were followed by a single large CSTR (rather than 14 further compartments). Also it was decided to determine whether any advantage existed in creating anoxia (no-aeration) in the first 2 compartments. To achieve these goals 3 reactor trains were set up in the fifth series of experiments: a control CSTR (Figure 1a), and two 3-compartment aeration basins each with 2 initial compartments 1/64th of the total aeration basin volume and a third with a volume equal to 62/64th of the total aeration basin volume (Figure 1h and 1i). In one of the 3 compartment units the 2 initial selector compartments were aerated with oxygen (DO = 4.5 mg/L); in the other, the 2 initial selector compartments were covered and stirred. The freeboard volume was purged with N_2 gas.

Figure 6 shows that the unit with two 1/64th volume aerated selectors reduced the SVI slowly and erratically to final values of 173 mL/g (at 2.5 g TSS/L) and 150 mL/g (at 1.5 g TSS/L). The final SVI value in the CSTR control and the unit with two 1/64th volume anoxic selectors was the maximum value possible (i.e., 400 mL/g at 2.5 g TSS/L and 667 mL/g at 1.5 g TSS/L). While the final SVI value in the aerated selector would still classify this sludge as a bulking sludge, these values were significantly lower than in

either the control or anoxic selector systems. Table 2 summarizes average operating data and initial and final SVI values for all experiments that employed selector configurations.

TABLE 2. OPERATING DATA SUMMARY FOR EXPERIMENTS EMPLOYING SELECTOR CONFIGURATIONS

Parameters	Units	Control CSTR	16 Compartment aeration basin					Two selectors + CSTR (Aerobic)	(Anaerobic)
V_T/V_i		1.0	32	16	32	74	16	64	64
Operation period	day	216	26	33	42	23	35	56	56
F/M	$\frac{\text{g COD removed}}{\text{g TMLVSS, day}}$	0.31	0.31	0.30	0.30	0.31	0.31	0.31	0.31
TMLSS	g/L	3.0	3.2	3.4	3.4	3.3	3.4	3.2	2.7
Average hydraulic Detention time	hr	19	17	18	19	20	21	21	.22
MCRT	day	15	14	15	14	12	13	12	14
Sewage strength	mg COD/L	720	620	660	720	745	790	830	830
$SVI_{2.5}$									
Initial	mL/g	96	98	78	373	389	46	400*	400*
Final	mL/g	400*	70	373	376	50	387	173	392
Initial Compartment F/M	$\frac{\text{g COD removed}}{\text{g MLVSS, day}}$	0.32	9.0	5.0	8.0	22.0	5.0	21.0	20.0
Soluble COD	mg/L	33	63	43	53	87	48	75	183

*Maximum SVI value at 2.5 gSS/L

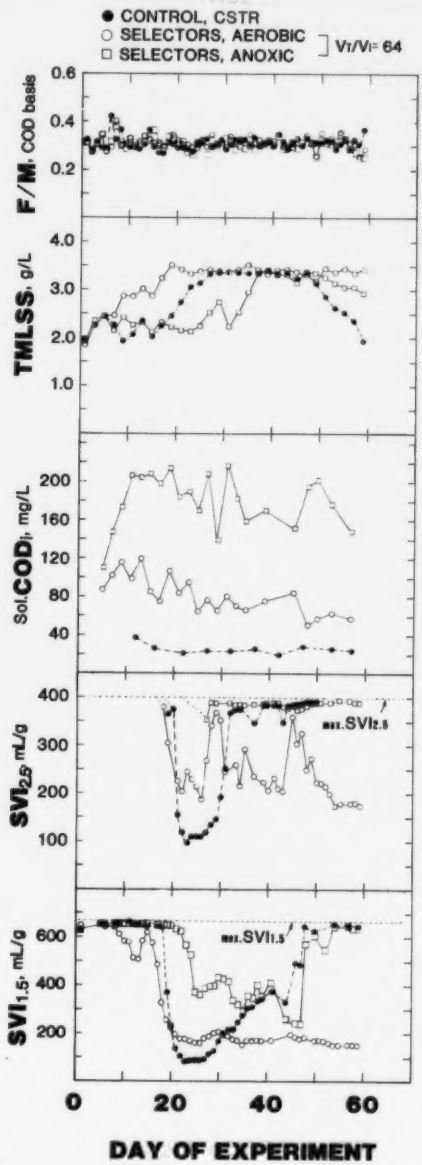

Figure 6. Experimental data; fifth series of experiments. Aeration basin configuration was two initial compartments each 1/64th of total aeration basin volume followed by a single compartment to bring total aeration basin volume to 42 L. In one system the initial selector compartments were aerated; in the second system they were stirred (anoxic). A CSTR control was used. RAS and sewage were fed to the initial compartment. F/M was 0.3 g COD/g TMLVSS, day. Starting with bulking sludge, the aerated selector unit produced some reduction in SVI while the anoxic selector unit SVI was not cured and the same as the control.

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SECTION 6

DISCUSSION

Bulking at low F/M did not occur when CSTR activated sludge systems were operated for 75 days with unsupplemented (weak) Richmond settled feed. With this feed, aeration basin TMLSS values were in the range 1.0-1.7 g/L and F/M was varied between 0.05-0.25 g COD removed/g TMLVSS, day; both fresh and stale settled sewage were fed. As soon as the TMLSS levels were raised to 3.0-3.5 g/L by feeding stronger sewage (supplemented with raw sludge) the CSTR units bulked. It would therefore appear that low F/M bulking is a phenomenon associated with strong (or raw) sewage feed and/or high MLSS levels. Further work is needed to separate the effects of these two parameters.

The effect of aeration basin compartmentalization on sludge settling is depicted in Figure 7. This plot is of the final SVI of systems that were started with bulking sludge. The plot shows that as the value of V_T/V_i increases above approx. 40, final SVI decreases rapidly. It would appear that for this system to produce a sludge with an SVI of below 100 mL/g, at least 2 initial reactors with volumes of 1/70th-1/80th or less of the total reactor volume are required. Previous workers (Chudoba, et al., 1973a, 1973b; Resink, et al., 1977; Tomlinson and Chambers, 1978) suggested a relationship exists (at low F/M) between SVI and the degree of longitudinal mixing; others (Tomlinson and Chambers, 1976, 1978; Eikelboom, 1981; Houtmeyers, 1978) have proposed that it is the presence of an initial high substrate level, where RAS and influent waste mix, that is important. It is argued that it is not important whether this is achieved by a reactor with a low degree of longitudinal mixing (i.e., many small compartments in series) or by one or more small reactors (initial mixing zones) followed by a larger completely mixed basin. The data presented here support the latter view since a plot of final SVI vs. the reciprocal of the dispersion number (uL/D) (Figure 8) does not produce the consistent relationship found in the plot of V_T/V_i and final SVI (Figure 7). Some workers (Chudoba, et al., 1973a, 1973b; Rensink, et al., 1977) have suggested that the COD gradient along a compartmentalized aeration basin is an important factor in controlling low F/M bulking. Others (Eikelboom, 1981; Tomlinson, 1976) have argued that it is the conditions (e.g., floc loading and soluble COD concentration) in the initial mixing zone that are important. Figure 9 relates the final SVI to soluble COD concentration in the first compartment. It shows the same consistent relationship as that between SVI and V_T/V_i. Figure 10 shows that apart from differences in the soluble COD concentration in the initial compartment, the soluble COD gradients throughout all of the systems examined were virtually identical. These data again support the view that initial compartment conditions are more important than changes in conditions

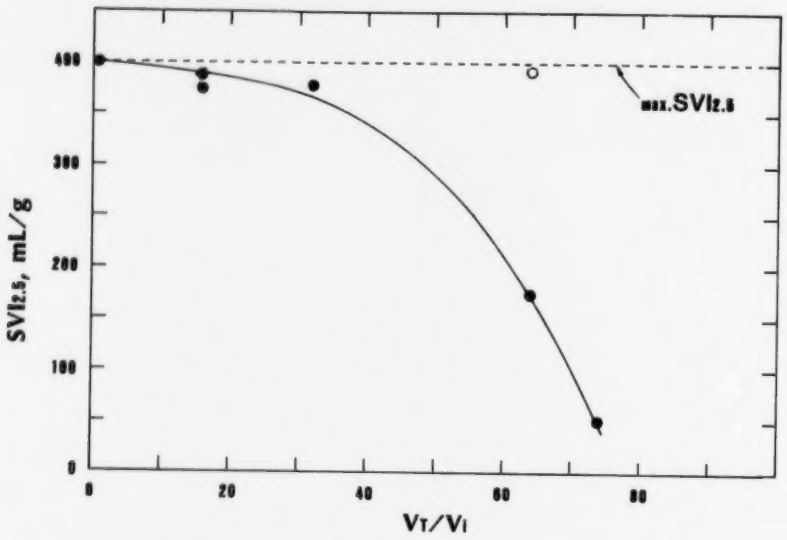

Figure 7. Relationship of final SVI (measured at 2.5 g TSS/L) to relative size of initial aeration basin compartment. (V_T = total aeration basin volume; V_i = volume of initial compartment; ●, for aerated initial compartments; ○, for anoxic initial compartments).

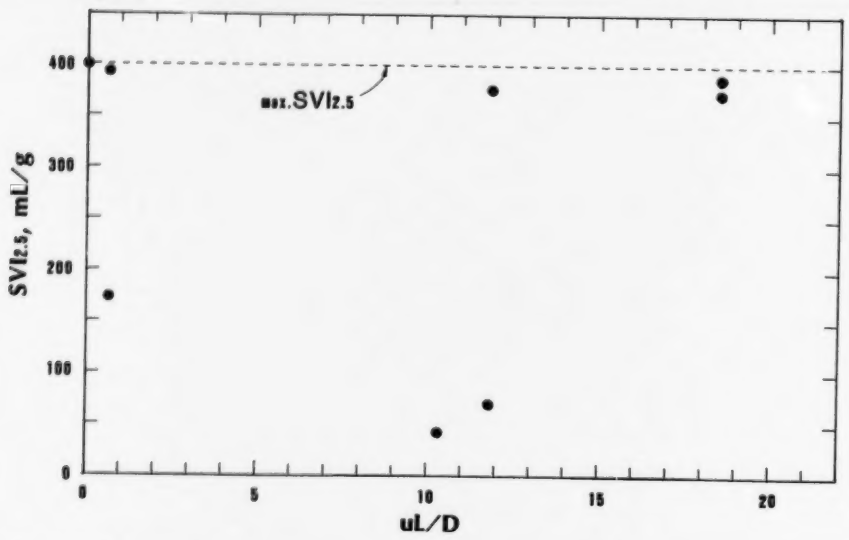

Figure 8. Relationship of final SVI (measured at 2.5 g TSS/L) to reciprocal of Dispersion number (uL/D) for aeration basin alone (no RAS flow or secondary clarifier included).

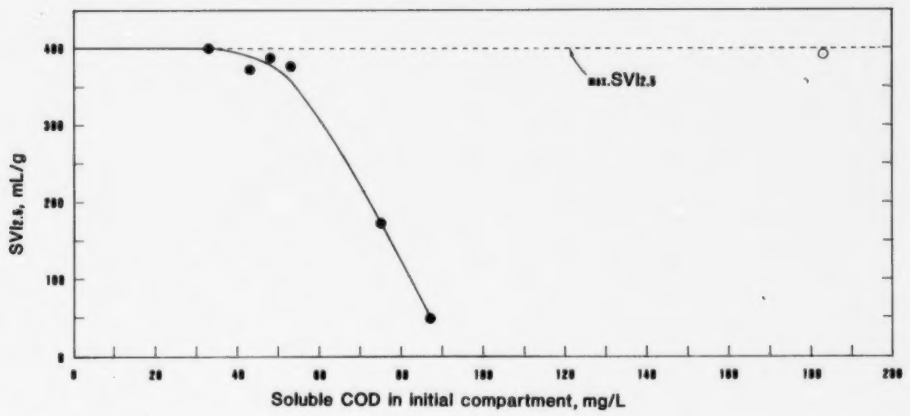

Figure 9. Relationship between SVI (measured at 2.5 g TSS/L) and soluble COD concentration in initial aeration basin compartment (● , aerated initial compartments; O anoxic initial compartments).

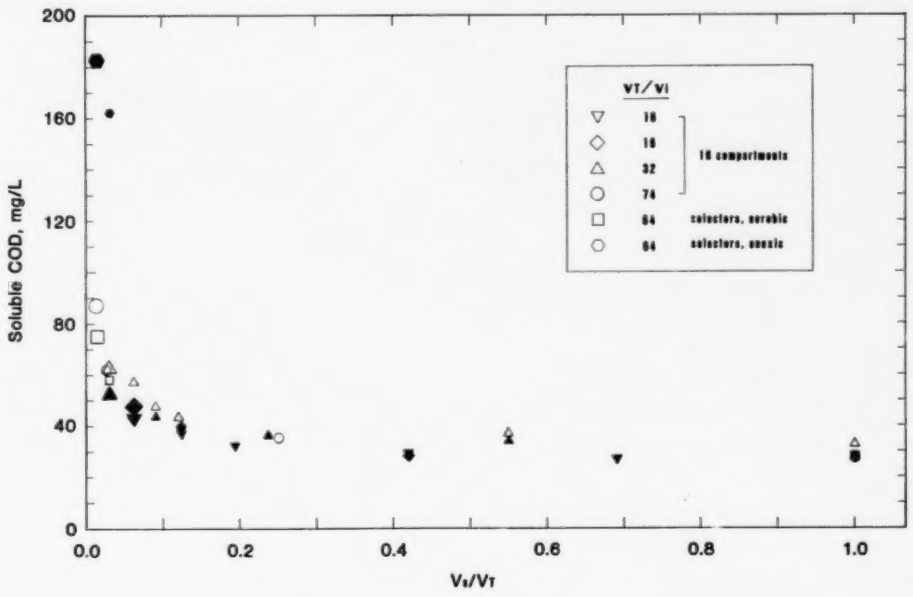

Figure 10. Soluble COD gradient throughout compartmentalized aeration basins. V_s/V_T is the fraction of the total aeration basin volume at the point of measurement. Solid points are systems that bulked; open points are systems that did not bulk. The large symbols are the soluble COD values in the initial compartment.

throughout the reactor. Figure 11 is a plot of the final SVI vs. F/M in the initial aeration basin compartment. Figure 12 shows the relationship between final SVI and the floc loading (Eikelboom, 1981). While there is a consistent relationship between SVI and initial compartment F/M (similar to that between SVI and initial compartment size and soluble COD concentration) no such relationship exists between final SVI and floc loading.

In the fifth series of experiments the following 3 reators were run:

a. Two initial oxygenated compartments each 1/64th of the total aeration basin volume followed by one compartment 62/64ths of the total aeration basin volume,

b. Same as a. but with both initial compartments stirred and anoxic,

c. CSTR aeration basin.

Systems b. and c. behaved equivalently (Figure 6) and had final $SVI_{2.5}$ at the maximum value of 400 mL/g; system a. final SVI was 173 mL/g. These results and the plots in Figures 7, 9, 10, 11 indicate that anoxia in the initial mixing zone was detrimental to the curing of bulking. Some literature sources (Heide and Pasveer, 1974; Tomlinson and Chambers, 1973; White and Tomlinson, 1978) have suggested that the initial anoxic zones where RAS and sewage mix successfully prevent and cure bulking at low F/M. Eikelboom (1981) recommends that the initial mixing zone be aerated both for mixing and because "biosorption" proceeds more rapidly than in anoxic basins; our data support this recommendation. Since the mixing conditions in our anoxic and aerated initial reactors were identical, we conclude that the effect of aeration was biochemical rather than physical.

All experiments were conducted with a constant recycle ratio (RAS flow/influent flow) of 1.0. Tracer studies indicated, as expected, that recycle increased longitudinal mixing (increased dispersion number) (Table 3). Recycle dilutes soluble COD concentrations in the initial reactor; the recycle ratio determines the contact time between sludge and influent in the first reactor and influences the floc loading in the first reactor. Eikelboom (1981) states that decreasing the recycle rate increases "biosorption" but decreases initial compartment COD removal. He suggests that there exists an optimum recycle rate corresponding to an optimum floc loading that produces optimum "biosorption". The influence of these factors was not addressed in this research because the recycle rate was constant. However, since the recycle ratio was maintained at the rather high value of 1.0, it can be concluded that the limiting sizes of the initial compartments found to be effective in curing bulking at low F/M are conservative, i.e., at lower recycle rates the initial compartment sizes could be larger. Further research is required to optimize the design parameters for initial compartment sizing.

Table 4 presents a summary of the predominant filamentous microorganisms present in the activated sludges from various series of experiments. In activated sludge systems with F/M = 0.16 g COD removed/g TMLVSS, day, Types 0041 and 0961 were predominant until the number of compartments was increased

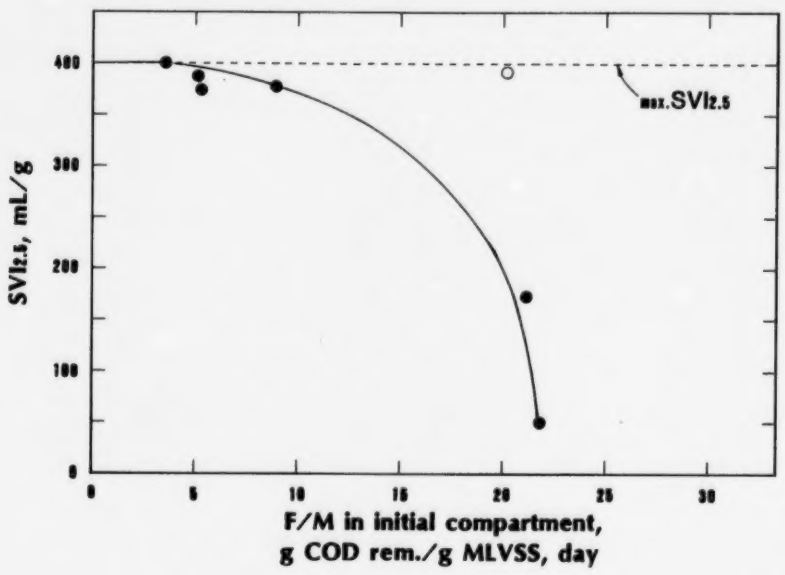

Figure 11. Relationship between SVI (measured at 2.5 g TSS/L) and F/M in initial aeration basin compartment.

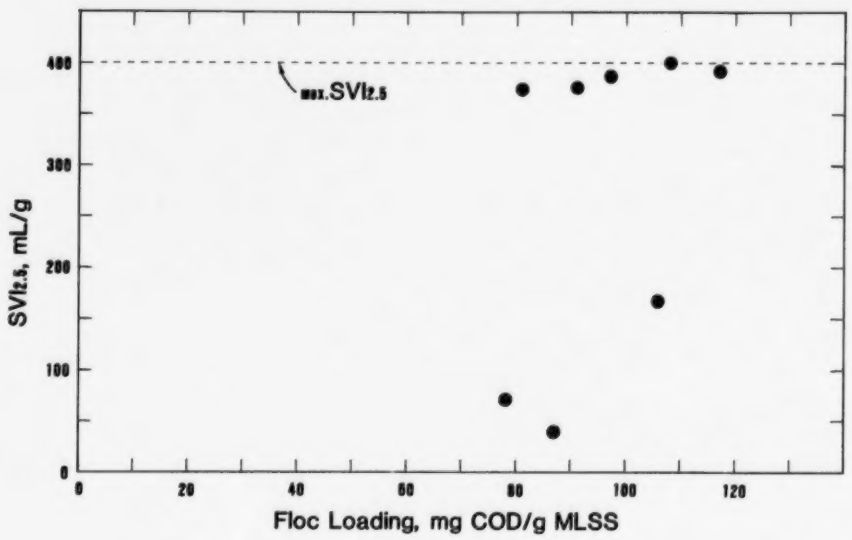

Figure 12. Relationship of SVI (measured at 2.5 g TSS/L) to floc loading (Eikelboom, 1981).

TABLE 3. EFFECT OF RECYCLE ON DISPERSION NUMBER OF VARIOUS AERATION BASIN CONFIGURATIONS

No. of Compartments	V_T/V_i	Dispersion number	
		Without recycle	With recycle*
1	1	∞	1.532
2	2	0.330	0.921
4	4	0.226	0.515
8	8	0.147	0.458
16	16	0.054	0.386
16	32	0.085	0.456
16	74	0.088	0.509
3	64	1.523	0.649

*Recycle ratio (RAS flow/influent flow) = 1.0.

to eight. At higher loadings and greater degrees of compartmentalization (and therefore smaller initial compartment size and higher initial F/M) Type 021N became common. At even higher loadings (F/M $\geq$ 0.74 g COD removed/g TMLVSS, day), Type 1701 and S. natans were present.

In the experiments conducted with various selector configurations at an F/M $\simeq$ 0.3 g COD removed/g TMLVSS, day, Type 021N was the most common filamentous organism. When the 2 compartment selector was employed, Thiothrix sp. was most common in both systems with aerated and anoxic selectors. S. natans and Type 1701 generally were more frequently found in significant amounts in the CSTR control than in the compartmentalized units.

These results are generally consistent with those of Chudoba (1973a) who found that bulking in a CSTR activated sludge unit was caused by a mixture of Leucothrix sp. (Type 021N?) and S. natans while bulking in a unit with an intermediate degree of mixing was caused by Leucothrix sp. (Type 021N?) alone.

TABLE 4. MOST COMMON TYPES OF FILAMENTOUS MICROORGANISMS IN ACTIVATED SLUDGE SYSTEMS

Experimental series	F/M (Avg.) ($\frac{g\ COD\ Rem.}{g\ TMLVSS,\ day}$)	Experimental system: No. of compartments	V_T/V_i	Min. DO* (mg/L)	Filament types	Control system: Min. DO (mg/L)	Filament types
1	0.16	1	1	2.5	--	2.5	--
2	0.16	1	1	2.5	0041, 0961	2.5	0041, 0961
	0.16	2	2	2.5	0961, 0041	2.5	0041, 0961
	0.16	4	4	2.5	0961, 0041	2.5	0041, 0961
	0.16	8	8	5.5	021N, 0961	2.5	0041, 0961
	0.16	16	16	7.0	--	2.5	--
3	0.24	16	16	7.0	--	5.5	0961, 021N
	0.39	16	16	11.0	--	5.5	021N, 0961
	0.53	16	16	16.0	021N, 0961	5.5	021N, 1701
	0.74	16	16	16.0	021N, 1701	9.0	S. natans, 1701
	1.00	16	16	16.0	1701, 021N	16.0	S. natans, 1701
	1.30	16	16	24.0	021N, 1701	24.0	021N, 1701
4	0.30	16	32	4.5	Nocardia, 0041, 021N	4.5	Nocardia, S. natans, 021N
	0.30	16	16	4.5	021N, Nocardia	4.5	021N, S. natans
	0.31	16	32	4.5	021N, 0961	4.5	0961, S. natans
	0.31	16	74	4.5	H. hydrossis, 0961	4.5	021N, 1701
	0.31	16	16	4.5	021N, 0581	4.5	0581, S. natans
5	0.32	3	64	4.5	Thiothrix, 021N	4.5	Thiothrix, 021N, 0961
	0.31	3	64	0.0	Thiothrix, 021N, 0581		

*Min. DO in initial compartment.

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